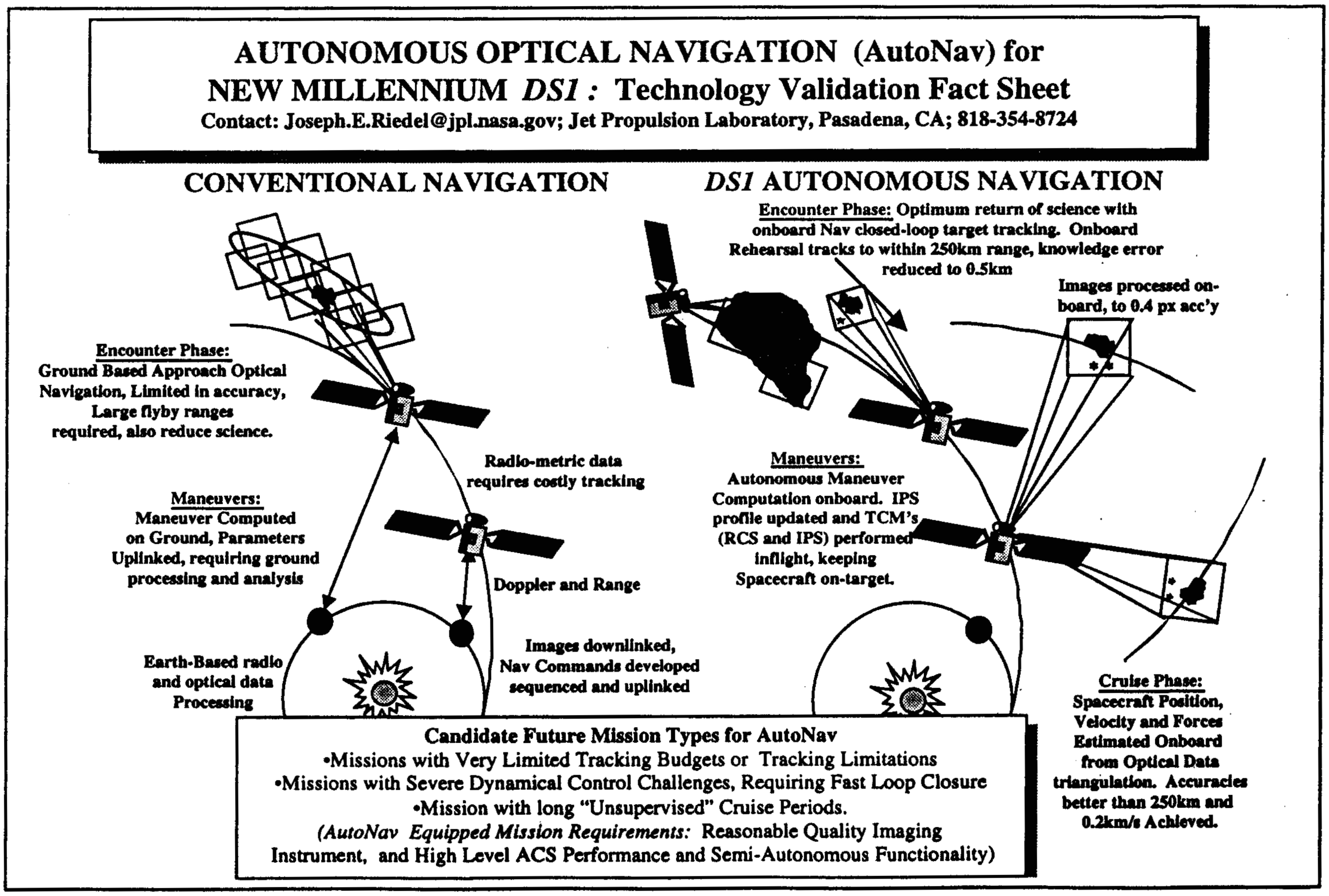
USING AUTONOMOUS NAVIGATION FOR INTERPLANETARY MISSIONS: THE VALIDATION *OF DEEP SPACE 1* AUTONAV

J. E. Riedel, S. Bhaskaran, S. Desai, D. Han, B. Kennedy, T. McElrath,
G. W. Null, M. Ryne, S. P. Synnott, T. C. Wang, R. A. Werner
Jet Propulsion Laboratory; 4800 Oak Grove; Pasadena, CA. 91109

Abstract

The first mission of NASA's New Millennium Program, *Deep Space 1*, has, as one of its principal demonstration-technologies, the first autonomous optical navigation system to be used in deep space. The AutoNav system is a set of software elements that interact with the imaging, attitude control and ion-propulsion systems aboard *DS1* in order to accomplish optical data taking, orbit determination, trajectory correction maneuvers, ion propulsion system (IPS) control, and encounter operations. The validation of this system in the flight of *DS1* to Braille was very successful. Despite very substantial problems with the *DS1* camera, the AutoNav system was eventually able to determine the spacecraft heliocentric position to better than 200km and .2m/s, as determined by ground-based radio navigation, which for this low-thrust mission, was itself a new technology. As well as achieving this principal goal of high quality interplanetary cruise orbit determination, AutoNav successfully completed many complex and difficult operations. These operations include provision of astronomical ephemeris data to non-navigational systems onboard, planning and execution of hours-long picture-taking sessions, planning and execution of sessions of ion-engine function, planning and execution of trajectory correction maneuvers, and successful completion of encounter activities during the Braille approach rehearsal, and for part of the actual approach, delivering the spacecraft to as close as 2.5km of the desired impact-plane-position, and starting encounter sequences to within 5 seconds of the actual encounter-relative start time.

Figure 1: Diagrammatic and Comparative Description of* DS1 *AutoNav



Introduction

Optical Navigation, as it is currently being applied by the deep-space probes of JPL/NASA is a technique by which the position of a spacecraft is determined through astrometric observations of targets against a background field of stars. The stars and target positions are known by ground or other observations, independently, or concurrently made, and the position of the spacecraft taking the image is inferred from the "error" in the position of the near-field object against the far-field, i.e. the parallax. In practice (of course) there are many complicating details. These include the numerical integration of the spacecraft trajectory, which requires accounting for adequate non-gravitational perturbation models in the spacecraft. Also to be provided is adequate accuracy in the star catalog, including accounting for proper-motion. Adequate calibration of the camera field-of-view distortions must be provided, as well as dynamic filtering of the acquired optical data, including stochastic estimation of pointing and spacecraft dynamic parameters; these among many other details.

Early demonstrations of optical navigation on deep space probes were performed on some of the later *Mariner* series, and the Mars *Viking* mission. But the first missions that required optical navigation to accomplish the principal mission objectives were the *Voyager 1 and 2* missions. The key technological developments for interplanetary optical navigation were made then (Ref. 1). Following the successful use of optical navigation, variations of this system were used for the *Galileo* approach and flybys of Ida and Gaspra (Ref 2), and during the *Galileo* Jovian tour. Due to a failure of *Galileo's* high-gain antenna, however, new technologies had to be developed for optical navigation, primarily to increase the information content from any single image. These new technologies include the multiple-cross-correlation technique, used for the Gaspra and Ida flybys, and an autonomous detection and capture algorithm loaded onboard to search through a navigation frame to find the target body (a Galilean satellite) and stars. Both of these algorithms were subsequently put to use onboard *DS1* as part of the AutoNav system.

Figure 1 shows a diagrammatic view of AutoNav, it's comparative advantages over and operational differences with conventional Earth-based radio-metric navigation. The principal advantages being the great reduction in navigation-required radio-link, and potential great increase in encounter data return.

Autonomous Optical Navigation was chosen as one of the prime technologies to demonstrate onboard *DS1*. Furthermore, it was accepted as the principal means of navigation for both cruise and encounter, operation of Ion Propulsion System (IPS), and execution of the encounter events. Since navigation of a deep-space probe using continuous low-thrust propulsion had never been done manually or autonomously, there were substantial challenges presented to the *DS1* AutoNav team. Additional challenges were the use of a new-technology imaging system (MICAS), and the development of operations techniques for a fully autonomous flight system (AutoNav) within the context of a conventionally commanded and sequenced spacecraft (Ref. 3).

AutoNav System Description

Overview

DS1 AutoNav is an onboard autonomous optical navigation system. When used onboard a spacecraft with an adequate imaging system, AutoNav is designed to autonomously determine the position of the spacecraft using images of distant asteroids. AutoNav then will compute changes to the spacecraft course using the scheduled IPS thrusting profile (if present) or with discrete TCMs. And finally, AutoNav will direct the terminal tracking activities at the closest approach. These high level activities are accomplished through the following actions and responsibilities:

- **Provide ephemeris information to other spacecraft subsystems.**
- **Plan and execute image taking sessions by:**
    - Developing an Image-Taking plan, from initial "suggested" target list.
    - Communicating with the ACS system, to get specifications of turns.
    - Executing turns, and requesting pictures be taken.
- **Process pictures, and reduce the image data to astrometric geometric information.**
- **Combine pictures into a data arc, and perform a batch-sequential least-squares solution of spacecraft position and velocity.**
- **Compute Course Correction:**
    - Propagate current spacecraft state to target and compute impact plane error.
    - If in a Mission Burn, compute changes to the burn direction elements, and burn duration.
    - If there is a TCM opportunity, compute the magnitude(s) and duration(s) of a TCM.
- **Execute a Mission Burn:**
    - Communicate with the ACS system for spacecraft turn specifications.
    - Turn the s/c to the correct attitude,
    - Start the main engine and maintain a Mission Burn with periodic direction updates

- Terminate the burn after the appropriate thrust has been achieved.
- **Execute a Trajectory Correction Maneuver**
  - Communicate with the ACS system for spacecraft turn specifications.
  - Turn the s/c to the correct attitude,
  - Start the main engine, or request that ACS perform a delta-v event.
  - Optionally, turn to a second TCM attitude and execute the second segment.
- **Perform Terminal Tracking and Encounter Operations**
  - Process close approach images of the target
  - Reduce and filter the picture data.
  - Estimate a target relative state, and communicate information to ACS
  - Start encounter sequences at the appropriate time.

Table 1 : AutoNav Functional Element Validation Summary

A	B: Technology Validation Item Description	C	D	E	F	G	H	I	J
1	Provision of Ephemeris Services	$\sim 10^5$	$\sim 10^5$	$\sim 10^5$	0	≤0.1km	Req'd	<<0.1km	<<0.1km
2	Opnav PhotoOp Process	~40	47	46	1				
3	Picture Planning	~40	47	47	0				
4	OpNav Data Accumulation, Handling, Downlink	~40	47	44	3				
5	Image Processing (RSS ensemble statistics)	~1200	~1500	~500	0	≤.25px	Desir'd	≤.40px	1.5px
6	Orbit Determination (Acc'y within data arc)	~32	34	34	0	≤250km, 1 m/s	Req'd	≤150km, 0.2 m/s	10000km, 7 m/s
7	Generation of Onboard Ephemeris, and Downlink	~32	34	34	0	.1-1km	Req'd	.1 km	1km
8	Trajectory Control and Maneuver Planning	~20	12	12	0				
8a	IPS Mission Burn Updates (Convergence criteria)	~12	6	6	0	≤1km	Desir'd	≤1km	≤1km
8b	IPS and RCS Maneuver Computations (do.)	~8	5	5	0	≤1km	Desir'd	≤1km	≤1km
8c	TCM Execution, and Delivery (Final TCM and accuracy – position and velocity)	8(2)	5(1)	5(1)	0	(≤2.5km, 0.25 m/s)	(Req'd)	(≤1.5km, 0.18 m/s)	(≤1.5km, 0.18 m/s)
9	Execution of Mission Burns	~12	7	7	0				
10	Encounter Image and OD Operations (RSEN)	2	2	1	0				
10a	Image Processing, and Data Reduction	~80	~80	~40	1				
10b	Ephemeris Generation and Delivery	~80	~80	~40	0	≤0.5km	Req'd	≤0.5km	15km
11	Encounter: Initiation of Encounter Sequences	8	8	8	0	≤5sec	Desir'd	≤5sec	≤15sec

Legend- A: Item Number (Appendix G), B: Item Description, C: No. Planned In-Flight Executions, D: No. Actual In-Flight Executions, E: No. Successes In-Flight, F: No. Failures In-Flight (due to AutoNav Fault and/or Misuse), G: Quantitative Goal-Value (If Applicable), H: Required/Desired Quantitative Value, I: Best Value Achieved, J: Worst Value Achieved

AutoNav Functional Element Descriptions:

Table 1 refers to a number of key elements of the validation plan that are broken out as individual items for which flight validation observables were expected and agreed to in the chartered technical validation strategy. Additionally, some of these items have quantifiable metrics, either delineated as requirements in the technology validation agreements with the project or internal requirements of normal spacecraft function, or strong "desirements" of the AutoNav Team. Also shown in the table is the number of executions of each of the elements planned pre-launch, the number of actual executions, and the number of successful and failed events. This table gives a concise measure of the extent of the AuotNav technology demonstration and the extent of its success. A description follows of the functional elements of the system shown in this table.

Provision of Ephemeris Services: This is the required function to provide various systems onboard (but chiefly ACS) information about the location of the spacecraft, and any solar system object of importance to the mission, such as Earth (for telecommunications purposes). *Opnav PhotoOp Process:* This is the overall "Photo-Op Machine" subsystem of AutoNav. It entails the coordination and execution of the following 3 sub-tasks. *Picture Planning:* This function retrieves the appropriate "suggested" selection of asteroid beacons from the Picplan File and determines those that are appropriate for imaging, given current mandated restrictions in the allowed viewing space of the sky. *ACS/APE Interaction & Turn Planning:* This function is the extensive network of interactions between AuotNav and ACS, and its planning subsystem APE (Attitude Planning Expert). ACS is queried for current states of the ACS system, and these results are used to construct the AutoNav sequences. APE is queried for turn specifications for the turns to the desired targets. *Mini-Sequence Picture/Turn/Fault Execution:* This function is the implementation phase of the Photo-Op. At the highest level, this function insures that all operations are completed in the allotted time. For picture taking and turning, mini-sequences are built with the desired commands, and launched into the sequencing engines (one of eight). Additionally, the progress of the Photo-Op is monitored, and excessive back-logs of unprocessed pictures are prevented. And finally, this function provides for contingencies in the event of one of a subset of failures of the Photo-Op, and recovery or abort action (short of calling the Fault Protection system (FP)).

Image Data Handling and Downlink: This Function accomplishes the MICAS picture data handling for AutoNav. This handling involves the compression, deletion and/or downlink of pictures as desired, with various levels of combinations of data quantity provided. *Image Processing:* As its name implies, this function is responsible for extracting useful navigation data from the onboard taken pictures. There are three stages to this process, an initial course registration, wherein the a priori prediction of the location of objects in the field, good to 10-20 pixels, is refined to 1-2 pixels, and then precision astrometry takes place, where the locations of objects are determined to (hopefully) 0.1 to 0.25 pixel. Finally, by using only the star images as reference, the inertial attitude of the camera when the image was taken is computed, and that information, plus the location of the target is written to the OpNav and subsequently the OD files. *Orbit Determination:* This is the purely computational function of reducing the suite of optical observations on the OD file to an estimated state of the spacecraft. Sub-elements of this function include numerical integration of the spacecraft position and velocity as well as partial derivatives of the spacecraft state with respect to dynamic parameters. Of course, estimation and filtering itself is a key function.

Generation of Onboard Ephemeris and Downlink: This function takes the freshly computed solution from the OD function, and integrates a new spacecraft ephemeris, produces a file (Spacecraft Ephemeris) of same and makes this file available to Ephemeris Services. This function is also performed after a maneuver plan. *Trajectory Control and Maneuver Planning:* This is the purely computational function of computing a course correction using a Mission Burn or a TCM. Computational elements involved in this function include iterative trajectory integration to compute a priori mistargeting, and numerical partial derivatives for the estimation of correction parameters. These parameters can be the elements of a discrete RCS or IPS TCM, or the direction and duration parameters for an IPS Mission Burn. Additionally, the Maneuver Planner must determine, through interaction with APE, whether a proposed TCM is "legal" in the context of spacecraft orientation constraints, and if not, provide a "vectorized" alternative.

TCM Execution and Delivery: This is the executive function of a TCM. Similar ACS, APE and mini-sequence interactions and operations as were described above take place here. This function must insure that all operations are complete within the allotted time, including turns to burn attitudes, executions of the burns themselves (either IPS or RCS), and a turn to the desired "home" attitude. *Execution of Mission Burns:* This function is that which accomplishes the operation of the IPS during the mission burns. There are several subfunctions, including ACS and APE interaction (much as was described for the Photo_Op and TCM functions) interactions with IPS (e.g. starting, stopping, pressurising, setting throttle levels and finally, safing the engine). Lastly, the Mission Burn function contains the overall management function of coordination of activities of the Mission Burn. This management includes evaluation of the navigation files to determine the proper direction and duration of the burning, and the starting and termination of the burns. *Encounter Image and OD Operations:* This function is the overall control and coordination function of the AutoNav close-approach Nav function, Reduced State Encounter Navigation (RSEN), and includes initiation and termination of RSEN mode, receipt and delivery of pictures to the RSEN picture processing module, and ultimate dispatch of the pictures following image processing.

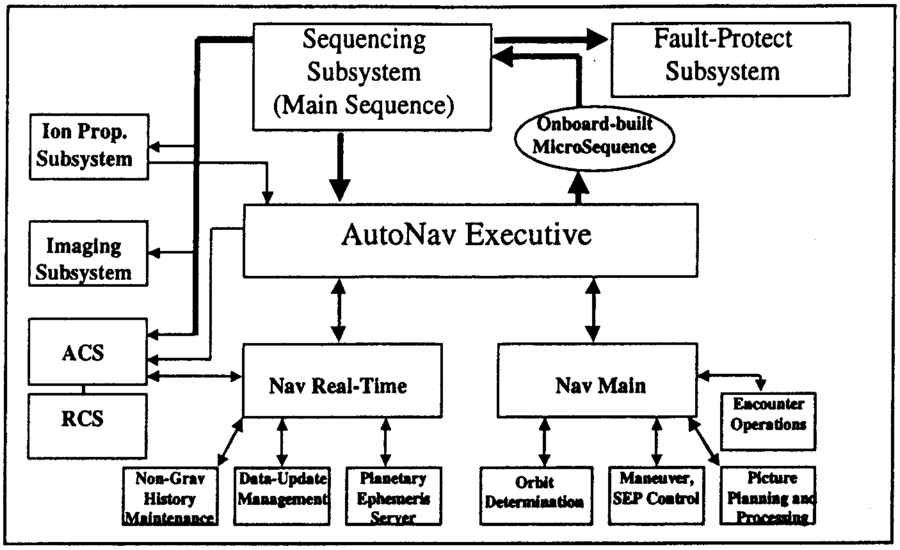
Computation (and Delivery) of Target Relative State: Given the successfully generated results of the image processing function described above, this function performs the reduced state orbit-determination operation and transmission of the data to ACS for tracking of the target. *Initiation of Encounter Sequences:* The final step in the encounter process is to start encounter sequences at a time appropriate for encounter science data gathering. During a close flyby of the target, the acquisition of navigation knowledge about the relative downtrack position of the spacecraft happens only very late. Consequently, parts of the close-approach science activity must be broken up into segments, generally getting shorter as they approach close-approach, and each of the these segments is started at an ever increasingly accurately determined time relative to close-approach.

AutoNav Software System

The AutoNav software is shown schematically in Figure 2. The AutoNav system is composed of three principle parts, the Nav Executive, Nav Main, and Nav Real-Time (NavRT). These communicate with each other and other subsystems through the underlying system messaging facility. Much of the commanding by AutoNav is through the sequencing subsystem, as will be discussed below.

Nav Executive: NavExec is AutoNav's director of spacecraft activities. It receives messages from other s/c subsystems and sends command directives, either through

Figure 2: The AutoNav Software System and Interacting System Software



the onboard sequence machine or through direct messages to other subsystems. When using the sequence subsystem (sequence engine), NavExec will build small sequences, and "launch" them. When NavExec needs an activity to occur immediately, for example to turn the spacecraft to a desired burn attitude, it will build a relative time sequence which the sequence engine initiates at once. Alternatively, when NavExec needs to insure that an event begins exactly at a certain time, it will build and initiate an absolute timed sequence, for example to cause the main engine to ignite for a TCM. NavExec contains three main state machines, for Photo-Ops, TCMs and for Mission Burns. These machines are mutually exclusive, the activities involved being clearly incompatible.

Nav Real-Time: NavRT is the subsystem of AutoNav that provides critical onboard ephemeris information to other onboard subsystems, but principally to ACS. NavRT operates at a much higher priority level in the flight-software than the other AutoNav components, due to the need to respond to sometimes frequent and time-critical ACS requests. NavRT also accomplishes file updates, involving ephemeris related files, by insuring that changes in files are completed in a way as to not jeopardize ACS ephemeris queries.

Nav Main: or just plain "Nav", is the central computing element of AutoNav. Requests for activity that involve large amounts of computing are directed to Nav by NavExec, or go to Nav directly through the command subsystem. These functions include picture processing requests from NavExec, Do-OD and ManPlan commands from ground commands. There are several important sub-functions of Nav: trajectory integration, which includes dynamic modeling of gravitational and non-gravitational forces acting on the spacecraft, data filtering, including a U-D factorized batch-sequential filter, and trajectory update computation, based on an iterative linear minimum-norm solution for changes to the IPS thrust profile to reduce projected targeting errors.

AutoNav Dependence on the *DS1* Imaging System (MICAS)

For *DS1*, the camera, like AutoNav is another technology being demonstrated. MICAS, the Miniature Imaging Camera And Spectrometer has two visual channels, a somewhat conventional CCD (Charge Coupled Device) detector and a much smaller APS (Active Pixel Sensor). Both of these channels are continuous read-out sensors, and are shutterless. The ability to take high quality astrometric images of small asteroids and image a bright inner solar-system target against a field of stars presents stringent requirements on a visual detector. The requirements listed in Table 2 were levied on MICAS during the design phase of the instrument, and the table indicates the level of success achieved in meeting these.

Table 2: Imaging System AutoNav Requirements and Attainment by MICAS

	Requirement Description	Value Required	MICAS value	Attained
1	Digitization level	≥10	12	yes
2	Field of View	0.6 to 2.0	0.7/0.25(APS)	yes/no
3	Array Size	≥512	1024/256(APS)	yes/no
4	Geometric Distortion/Errors	≤2μ-radians	7 μ-radians	no
5	Device fullwell and noise	80,000 e⁻/50 e⁻	35,000 e⁻/40 e⁻	no/yes
6	Dimmest obtainable image	12M	9.5M	no
7	Long-Exposure Capability	200sec	5-100sec	no
8	Encounter Imaging	Target and 9M	Target and 7M	no

Eight months before the launch of *DS1*, it was discovered that the CCD channel had a severe limitation when imaging bright objects (objects as bright as the first two expected targets). When an object of a typical asteroid brightness subtended more than 100 pixels (+/- 50), severe charge bleed appeared in the picture due to the inability of the CCD read-out to cope with the continuing photon flux during the read-out. Because of this limitation, it was believed that the CCD channel would be unusable during the last few minutes of approach. Figure 3 shows an example of the phenomena, taken during the instrument check-out, pre-launch.

Figure 3: MICAS Extended Bright Image Charge Bleed

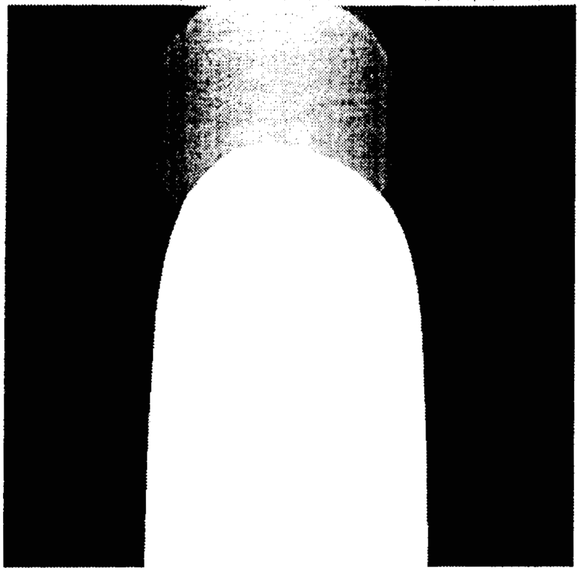
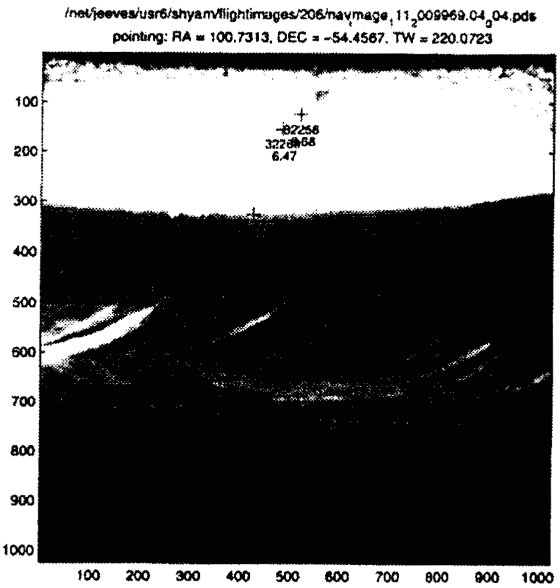


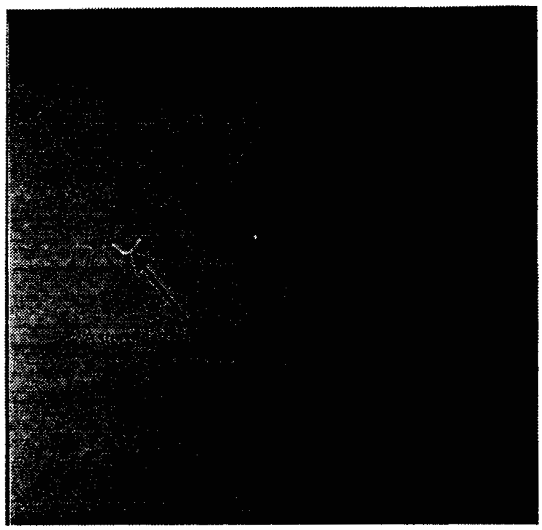
Figure 4: MICAS "Low Solar Cone Angle" Scattered Light Picture



As a result of this problem, the less capable APS channel was used by AutoNav on approach. In partial compensation, the read-out time required for the APS was much shorter than for the CCD, 2 seconds vs. 20 seconds. At the first use of MICAS it was apparent that there were substantial light scattering problems around and in the camera (Ref. 4). Depending upon the sun-relative geometry, the CCD would saturate (achieve maximum measurable charge) in as little as 5 seconds of exposure.

In view of the fact that the original feasibility analysis of AutoNav called for exposures as long as 200 seconds, this clearly represented a reduction in capability by limiting usable geometries and targets. Figures 4 and 5 show two examples of the scattered light effect in roughly normal-to-sun and anti-sun geometries. Despite these severe difficulties however, asteroids were still visible. In Figure 5 are indicated asteroid Vesta (7^{th} Magnitude in this image) and a star (8^{th} Magnitude). With substantial upgrades to the AutoNav software, other dimmer asteroids and stars were eventually obtainable and autonomously processable, as will be discussed below. A third difficulty with the camera is a highly non-linear response curve (Figure 6.) The net effect of this

Figure 5: MICAS "High Solar Cone Angle" Scattered Light Picture

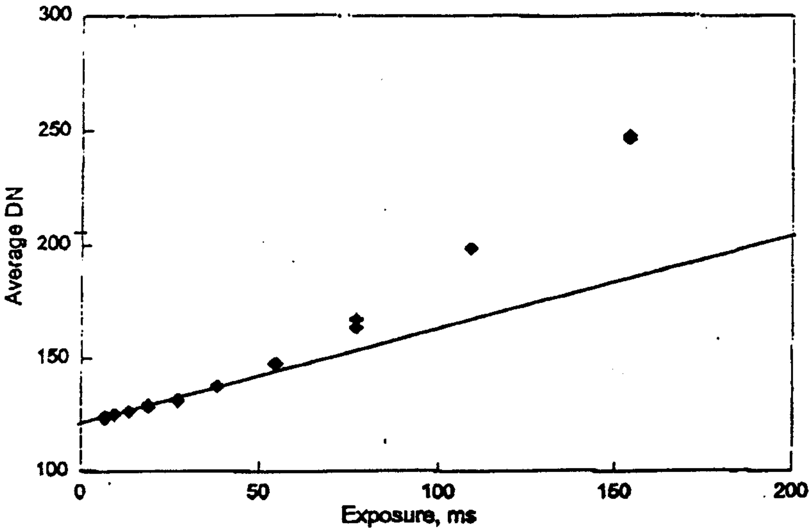


electronics fault is for low flux signals to be non-linearly attenuated. This effect is much more severe in the APS, and largely accounted for abnormally low throughput at the Braille encounter. Yet another substantial difficulty for AutoNav arose due to light-attenuating scratches in the optics-chain over a substantial portion of the CCD center of field-of-view. These blemishes are partially shown as the dark streaks and patterns in the center and center top of Figure 5.

AutoNav Technology Validation

The overarching philosophy behind AutoNav testing, was to initially ground test every operation of AutoNav under normal and a selection of abnormal circumstances. Once in flight operations, the first few events of a given Nav operation were always tested on various testbeds thoroughly. Only after several successful operations under this closely simulated test restriction were the

Figure 6: MICAS APS Channel Non-Linear Signal Response



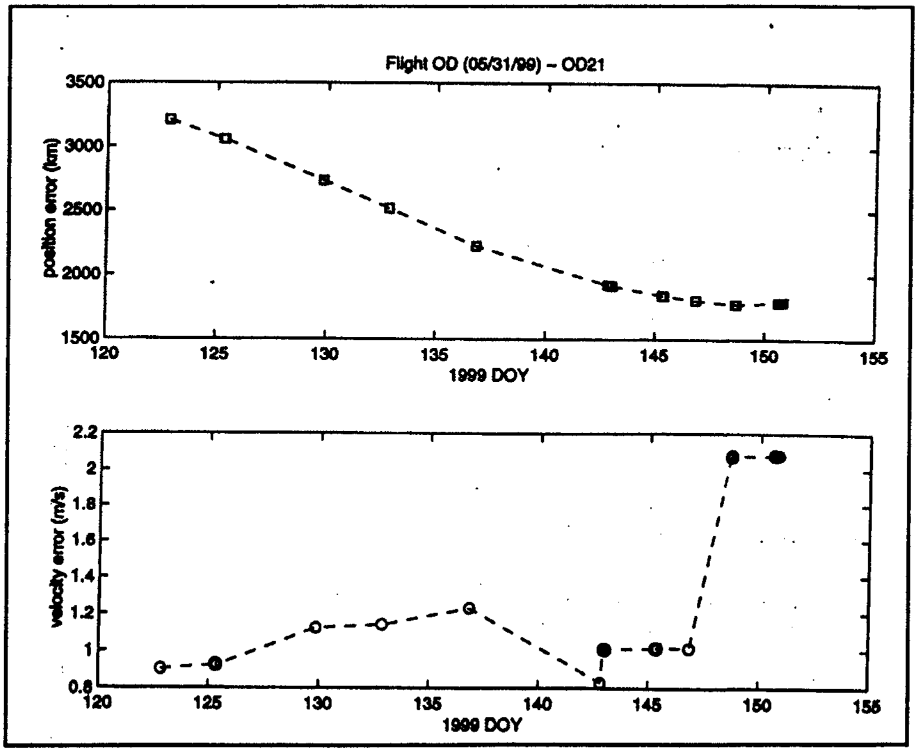
autonomous systems allowed to operate without a very well tested predict of the expected outcome. The principal difficulty in this strategy was the early almost complete lack of predictability of the behavior of the scattered light and leakage within the MICAS camera. As is discussed in the body of the report, this problem caused general failure of the image-processing algorithms, depriving subsequent functions of data, altering the expected behavior of the AutoNav sessions. In no case however, was this inability to predict considered to be, nor did it at any time prove to be a hazard.

Table 1, a summary of AutoNav validation plans and success, gives a succinct summary of all of the validation events undertaken. Where applicable, quantitative goals and achievement levels are listed. In general, there is a range of achievement in these values, and where this is so, best and worst values are noted.

The concept of an autonomous optical navigation system was proved early in the mission development phase using a MATLAB® simulation of a ballistic mission to an asteroid. This demonstration simulated pictures taken in flight by such a mission, processed those pictures and used the reduced data in a orbit-determination estimation process. Subsequently, maneuvers were computed to control accumulated errors in the simulated orbit due to OD errors, non-gravitational model errors and perturbations. Finally, the encounter was simulated, with late tracking and orbit updates of the target. Results from this simulation gave strong indication that orbit quality of better than 500km and 0.5 m/s was possible during the cruise phase, as well as delivery at the target to better than 10km (Ref 5).

As the actual flight system began to develop, tests were on-going, covering a wide range of expected mission operating conditions. Early in this process, the decision was made to make *DS1* a low-thrust mission, requiring a substantial increase in the complexity of AutoNav. Extensive new theoretical development and test was required as a result (Ref. 6). Of a large number of missions considered and partially evaluated, a mission to asteroid McAuliffe, then Mars, followed by a flyby of comet West-Kahotek-Ikamoura was settled upon, and extensively evaluated. The extensive cruise phases were simulated and OD performance evaluated, and the ability of the maneuver planner to keep the spacecraft on course was robustly demonstrated. (This mission was subsequently replaced by the current 1992KD, Wilson-Harrington, Borelly mission, due to a required launch delay). None of these tests gave performance and capability results in conflict with the prototype demonstration phase.

Figure 7: Flight vs. Ground Orbit Determination, May 31, 1999



Each of the elements of AutoNav went through stand-alone tests and extensive system tests as part of the delivery process of each new version of the software. The system tests covered various mission phases, and all of the interactions and functions of Nav. Additionally, AutoNav systems, particularly the ephemeris services, were required for all other system tests, leading implicitly to additional Nav verification. None of these tests gave performance and capability results in conflict with the prototype demonstration phase.

Upon the first invocation of the higher AutoNav functions in flight, in November of 1998, it was obvious that pre-flight performance estimates would not be met; this was almost entirely due to the problems encountered with MICAS. Because of the scattered light leakage problems it was impossible to successfully acquire navigational data onboard before extensive AutoNav flight-software modifications were performed. However even ground processing of the onboard acquired images revealed problems, keeping the performance of the system (as demonstrated on the ground) above 5000km and 2m/s (Figure 7). Nevertheless, all other subsystems of AutoNav, including autonomous picture-taking planning execution, IPS mission burn planning and execution, orbit determination with ground-seeded data performed well.

By June, 1999, all modifications had been made to the cruise AutoNav system, including image processing changes to deal with the scattered light-leakage problems, and severe geometric distortions observed in the camera field. With these changes and calibrations onboard, the performance of the onboard cruise navigation on several occasions met the original cruise AutoNav validation agreement values of better than 250km and 0.5m/s. However, due to the continuing uncertainty of the geometric distortions, this could not be continuously maintained autonomously onboard, but could through hand editing of data on the ground and subsequent upload of the edited data sets; see Figure 8. But this performance was sufficient to continue with the validation schedule and use AutoNav for approach to Braille.

On July 13 1999, just 16 days before closest approach a full onboard "dress rehearsal" of the encounter was performed, with AutoNav simulating the encounter with a "pseudo-Braille," autonomously computing and executing one of the two approach TCM's, and delivering the spacecraft within 2.5 km of it's fictional target. AutoNav also started encounter sequences as close as 5 seconds to the nominal encounter-relative start time. All subsystems executed perfectly, and the *DS1* team as well as AutoNav were primed and ready for the actual approach.

Figure 9 shows a series of solutions from the onboard AutoNav system and from the radio navigation system on the ground used to develop the Encounter–5day TCM. TCM's at –20 and –10 days were cancelled due to the relative stability of both flight and onboard solutions and nearness to the desired target position. These solutions were all made before the initial onboard sighting of Braille, and were based only on *a priori* estimates of the asteroid ephemeris. Two such pre-encounter ephemerides are shown. Also shown is the close agreement of the ground radio and AutoNav solutions. The 7/22 AutoNav Flight Solution was used onboard to compute a TCM labeled "B", virtually identical to the ground computed solution based on "G". The following day, the flight solution had shifted to "F2", and a new encounter-5 day burn was computed, but due to an anomaly with the onboard file system, solution "B" was reverted to. It was felt that this solution left the spacecraft within 200km of the proper target conditions.

After the "-5 day TCM" there were TCM opportunities scheduled at –2d, -1d, -18h, -12h, -6h and -3h. Throughout this time, observations were scheduled to allow AutoNav the opportunity to attempt a detection of Braille. Because of the non-linearity of the imaging

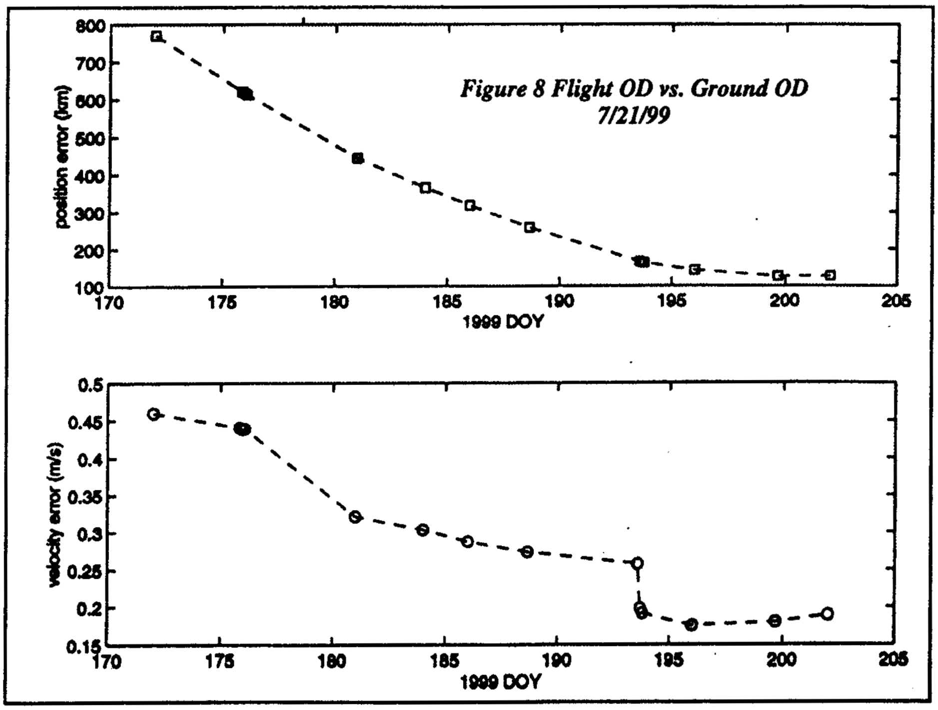


Figure 8 Flight OD vs. Ground OD 7/21/99

system and the inability to take long exposures due to scattered light, the first detection of Braille wasn't made until encounter -2.5 days. This detection was only by ground operators however, due to the faintness of the

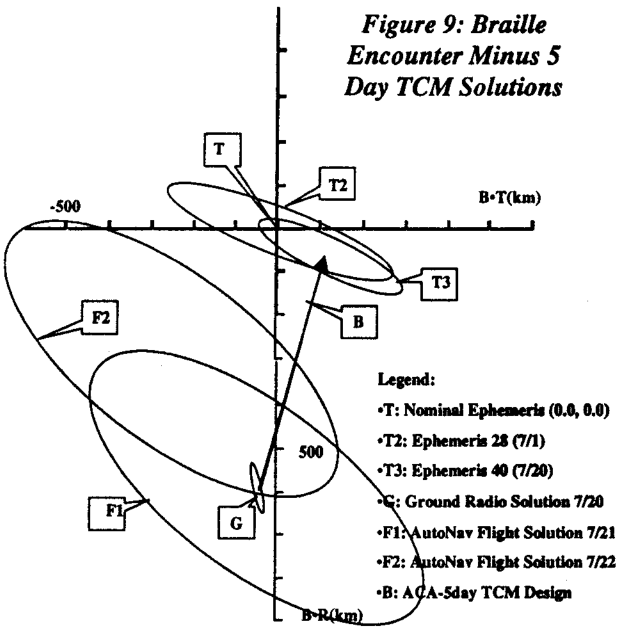


Figure 9: Braille Encounter Minus 5 Day TCM Solutions

signal. However it showed a 350km ephemeris shift (approximately 2 sigma). Because of this large shift, and the faintness of the observation, the –2d TCM was cancelled (AutoNav would normally decline to execute a TCM if it was statistically insignificant, but because of the data difficulties associated with the geometric corrections, it was decided to actively prevent this execution). In subsequent observations, the dim "phantom image" turned out to be true, but remained anomalously feeble (due to the previously discussed camera non-linearity). As a result, AutoNav was unable to "lock-on" to Braille prior to the "-1 day" TCM, and 5 hand-located Braille images were used to design this TCM, shown in Figure 10. The –1day TCM was completely nominal, and at –18hours, a photo-session was performed in which AutoNav finally "locked on" to a sufficiently bright Braille image, and was proceeding to compute the –12 hour TCM when a software fault caused the spacecraft to "safe". It took almost 10 hours to recover the spacecraft into normal mode, during which time 3 of the surviving pictures from the photo-session were downlinked and used to compute the -6 hour TCM. This data was uplinked to the spacecraft and it was set on its way for the final 6 hours of autonomous operations.

Because of the bright-image bleed problems with the CCD, it was necessary for AutoNav to switch detectors to the less capable and less well characterized APS channel shortly before encounter. With nearly all of the science and all of the Nav data scheduled from this sensor within 30 minutes of closest approach, the approach sequence was extremely dependent upon models that described the expected brightness of the approaching target. In the event, the target was far dimmer than expected for at least two reasons. First, the photometric predictions were inaccurate due to inextendability of the assumed models to the encountered geometry, and the lack of allowance for an inopportune presentation of an oblong object to the approaching spacecraft. Second, the APS sensor exhibits extreme non-linearity at low signal, causing a flux dimmed by the first phenomena to have its signal obliterated. As a consequence, no useable signal was received, and effectively, close-approach AutoNav did not operate during the Braille encounter.

Despite the fact that the performance of the system during the Braille flyby was thwarted, it is nevertheless the case that operability and accuracy of the AutoNav close-approach system had been demonstrated in the testbeds, and more importantly in-flight during the rehearsal. This was proved in the real case using the few acquired CCD images of Braille post-encounter. When these were provided to AutoNav, accurate solutions of the spacecraft position were obtained with just 1 CCD image, leading to the unavoidable conclusion, that had this detector been used, instead of the APS, the encounter would likely have been very successful. Fig. 11 shows the B-plane results of this analysis. Figure 12 shows one of the post-encounter APS science images taken 15 minutes after closest approach (Braille is the dim smudge center-left). Despite the fact that Braille appeared several times brighter outbound than inbound, this signal is barely detectable, strongly indicating that the approach APS images available to AutoNav had no discernable images.

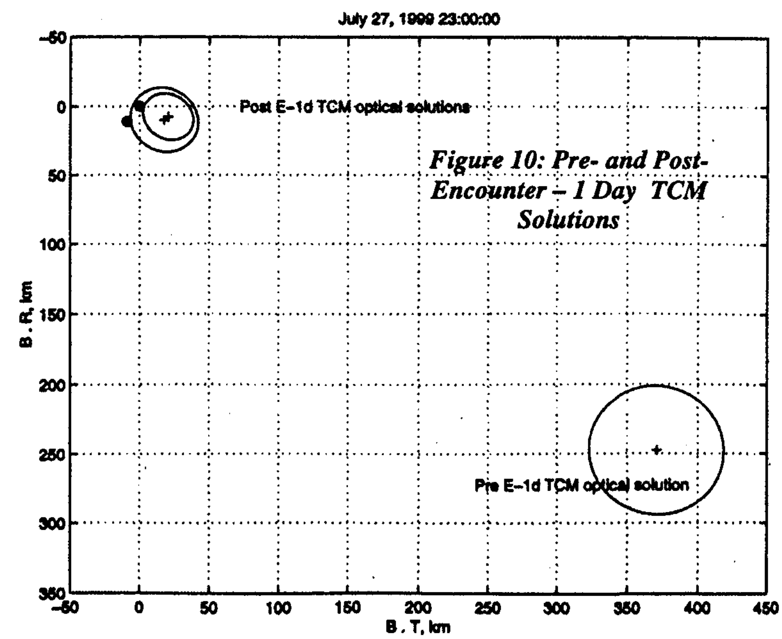


Figure 10: Pre- and Post-Encounter – 1 Day TCM Solutions

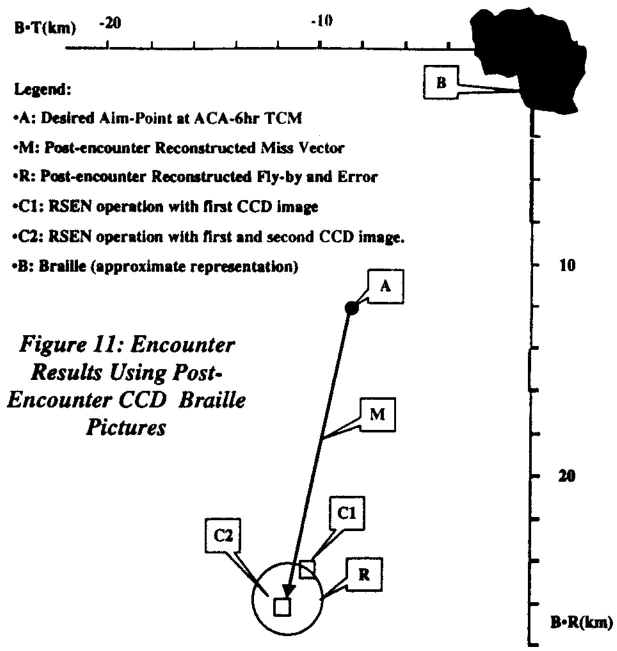
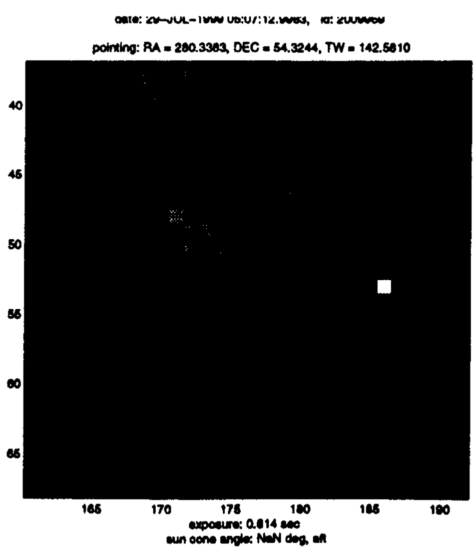


Figure 11: Encounter Results Using Post-Encounter CCD Braille Pictures

Conclusions

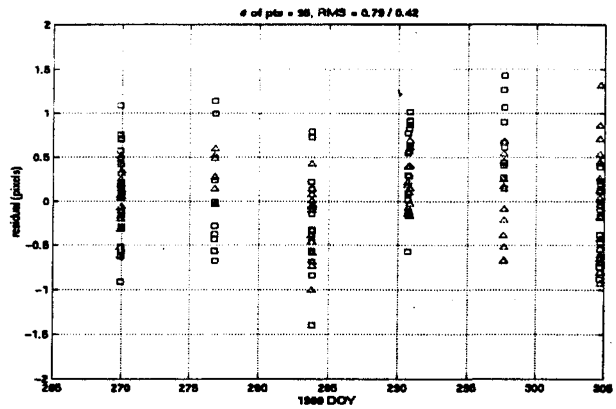
Despite the disappointment of the Braille encounter, the overall success of the DS1 technology validation mission must be rated very highly. In a period of little over 9 months, several advanced and complex technologies were validated while a spacecraft was kept on course for an interplanetary encounter, and achieved that encounter. AutoNav shared fully in that success, and perhaps the best measure of that occurred in the two months immediately following Braille encounter. Then, the *DS1* Navigation team enjoyed the advantages of its work, as the system was invoked and allowed to navigate the spacecraft without intervention. These results, optical residuals from several dozen asteroid observations, are shown in Figure 13. These represent excellent results by any measure.

Figure 12: Post-Encounter APS Image of Braille



Interplanetary navigation autonomy was achieved: *DS1* determined her own course while the Nav team got a well deserved vacation!

Figure 13: Post-Braille AutoNav Data Arc and Residuals



Acknowledgements

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

1) J. E. Riedel, et al "Optical Navigation During the Voyager Neptune Encounter", AIAA paper 90-2877-CP, AIAA/AAS Astrodynamics Conference, Portland Oregon, August 1990.
2) R. M. Vaughan, J. E. Riedel, R. P. Davis, W. M. Owen, S. P. Synnott, "Optical Navigation for the Galileo Gaspra Encounter," AIAA paper 92-4522, AIAA/AAS Astrodynamics Conference, Hilton Head, South Carolina, August 1992.
3) J. E. Riedel, et al, "Navigation for the New Millennium: Autonomous Navigation for *Deep Space 1*", SP-403, 12th International Symposium on 'Space Flight Dynamics', ESOC, Darmstadt, Germany, June 1997.
4) R. J. Koshel, G. Peterson, "Stray Light Analysis of MICAS," BRO Report #3580, September 1999, Breault Research Organization, Inc, Tucson Arizona.
5) S. Bhaskaran, et al., "Orbit Determination Performance Evaluation of the *Deep Space 1* Autonomous Navigation System", AAS 98-193, AAS/AIAA Space Flight Mechanics Meeting, Monterey, California, February 1998.
6) S. D. Desai, et al. "The *DS1* Autonomous Navigation System: Autonomous Control of Low Thrust Propulsion System", AAS Paper 97-3819, AAS Conference, New Orleans, Louisiana, August 1997.